METHOD AND APPARATUS INCLUDING IN-RESONATOR IMAGING LENS FOR IMPROVING RESOLUTION OF A RESONATOR-ENHANCED OPTICAL SYSTEM

RELATED APPLICATIONS

This application is a continuation-in part of U.S. Patent Applications "OPTICAL STORAGE METHOD AND APPARATUS HAVING ENHANCED RESOLUTION", serial number 09/871,512, filed May 30th, 2001; "OPTICAL MEASUREMENT AND INSPECTION METHOD AND APPARATUS HAVING ENHANCED OPTICAL PATH DIFFERENCE DETECTION", serial number 09/933,225, filed August 20th, 2001; and "OPTICAL INSPECTION METHOD AND APPARATUS HAVING AN ENHANCED HEIGHT SENSITIVITY REGION AND ROUGHNESS FILTERING" serial number 10/002,425, filed October 23rd, 2001. The specifications of all of the above-listed parent applications are incorporated herein by reference.

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to optical systems, and more specifically, to an optical system incorporating a resonator to enhance the resolution of optical inspection systems and other optical devices.

2. Description of the Related Art

Optical measurement systems, optical storage and retrieval systems and other optical systems may be limited by many factors, including effective detector and illumination resolution. The effective resolution of a detection system is often set by the diffraction limitations of the system. The above-incorporated patent applications disclose techniques for enhancing the performance of a variety of optical systems and improving the resolution of optical technologies disclosed therein.

While incorporation of a resonator within an optical system can provide an improved resolution due to reduction in illumination beam size and/or detection sensitivity of the system, there are limitations on the resolution improvement that may be obtained due to divergence and losses at each internal reflection. If perfectly perpendicular-to-mirror multiple reflections existed in the resonator to support the resonance condition, the resonator would be ideal. However, due to the finite non-zero propagation distance within the resonator caused by microscopic surface variation on the mirrors, as well as by diffraction effects, the internal reflections will deviate from the ideal resonator geometrical optics model of both linear and perpendicular propagation between the mirrors.

It would therefore be desirable to improve the performance of the resonator-enhanced optical systems disclosed in the above-referenced patent applications, as well as other optical systems, in order to further improve their resolution and performance.

SUMMARY OF THE INVENTION

The foregoing objectives are achieved in an improved optical resonator apparatus and optical system having improved resolution performance along with a method for improving resolution in an optical system. The optical system includes a resonator positioned within a pathway of a measurement beam of the optical system. The resonator includes at least one imaging lens for imaging a point or area of one of the reflective surfaces of the resonator on to a point or area of a second reflective surface. The second reflective surface may be one of the resonator (resonant) surfaces, or the second reflective surface may be an intermediary surface and the resonance may be supported with respect to a single reflective surface of the resonator imaged onto itself.

Inclusion of the lens(es) reduces the optical imaging distance of the resonator to zero by imaging the two mirrors onto each other, while the propagation distance can be any chosen value. Reducing the optical imaging distance to zero improves the performance of the resonator by essentially eliminating the divergence between the multiple internal reflections.

One of the resonator reflective surfaces may be incorporated on a planar surface of the imaging lens, or provided as a separate partially reflective coated plate.

The foregoing and other objects, features, and advantages of the invention will be apparent from the following, more particular, description of the preferred embodiment of the invention, as illustrated in the accompanying drawings, wherein like reference numerals indicate like elements.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is an optical schematic depicting a resonator in accordance with an embodiment of the invention.

Figure 2A is an illustration depicting an optical resonator in accordance with a first resonator embodiment of the invention.

Figure 2B is an illustration depicting an optical resonator in accordance with a second resonator embodiment of the invention.

Figure 2C is an illustration depicting an optical resonator in accordance with a third resonator embodiment of the invention.

Figure 3 is an illustration depicting an optical system incorporating a resonator in accordance with a first system embodiment of the invention.

Figure 4 is an illustration depicting an optical system incorporating a resonator in accordance with a second system embodiment of the invention.

Figure 5 is an illustration depicting an optical system incorporating a resonator in accordance with a third system embodiment of the invention.

DETAILED DESCRIPTION OF ILLUSTRATIVE EMBODIMENT

The above-incorporated patent applications describe various resonator-enhanced optical systems, such as optical storage data and retrieval systems having improved data density, optical measurement systems having improved resolution and contrast, and optical systems having improved detector phase/amplitude slope characteristics controlled over portions of the detector response. The above-recited improvements are developed by placement and tuning of resonators within the optical paths of the associated systems.

The present invention concerns a method and resonator apparatus that further improve performance of a resonator-enhanced optical system by incorporating one or more imaging lenses within the resonator, causing the resonance at a single point (in practice, a very small area) or region on one or more of the reflective surfaces forming the resonator. The present invention therefore provides an improvement in all of the above-mentioned resonator-enhanced systems, as well as other systems incorporating resonators where improved resonant performance at a particular detection point is desirable. Imaging a resonance over a very small area (point) has another advantage, in that

sensitivity to surface tilt is dramatically reduced (in theory, for a single point on a surface, surface tilt is irrelevant).

With reference now to the figures, and particularly to **Figure 1**, an optical schematic of a resonator in accordance with an embodiment of the invention is illustrated. Resonance is supported between mirrors **M1** and **M2**. At least one of mirrors **M1** and **M2** is generally partially reflective, to allow coupling to the exterior of the cavity formed between mirrors **M1** and **M2**. A lens **L** images the mirrors **M1** and **M2** onto each other (for exemplary purposes, a 1:1 magnification is illustrated). Any ray **A** illuminating mirror **M1** at the point **P** provides a partially transmitted ray that is collected by lens **L** and imaged from point **P** of mirror **M1** at point **P′** of mirror **M2**. Beams reflected from point **P′** return through lens **L** to mirror **M1** and are imaged at location **P**. The reflections are supported over an angular space that reaches to the angle (in actuality forming a cone) where a larger angle ray will not be collected by lens **L**. Other rays introduced at points other than **P** and/or **P'** will establish a resonance between two corresponding points on the mirrors **M1** and **M2** within the field of view of lens **L**. Mirrors **M1** and **M2** form a resonant optical cavity that is also an imaging system. Each object/image point pair within a field of view of lens **L1** resonates independently from all other points within the

limitations of the resolution of lens **L1**. Lens **L1** thus produces a "resonant image" between the two mirrors. Illumination can be spatially coherent or provided from a finite source. The resonant image described above can be coupled outside of the cavity through either (or both) of mirrors **M1** and **M2** and projected or imaged by known techniques onto a detector, camera, eyepiece, or other vision system.

When one of mirrors **M1** or **M2** is a surface of interest (e.g., the surface of interest is coated with a reflective coating), or a target/object surface, amplitude and phase at the surface of interest will be accurately reproduced at the other mirror due to the resonance effect. The amplitude and phase matching greatly increases spatial as well as height resolution distribution of the field in the object mirror (or surface of interest) that is reproduced at the image mirror. An optional mask **MA2** may be incorporated into or placed directly in front of one of mirrors **M1** or **M2** (in the exemplary illustration mirror **M2**). The image on mask **MA2** (such as a photo-lithographic image) will be reproduced at mirror **M1** and due to the resonance established between mirror **M1** and mirror **M2**, the image will be reproduced with virtually no degradation.

With reference now to the other figures, and particularly to **Figure 2A**, a cross section of a resonator in accordance with an embodiment of the invention is depicted. The depicted embodiment is used in systems where illumination is provided from a coherent collimated source (e.g., source at an infinite distance/infinite conjugation ratio). In the configuration of **Figure 2A**, all incoming rays are parallel to the optical axis of the system. The resonator includes a partially reflective surface **12A** shown as a coating deposited on a plate **12** and a second surface, which is generally a surface under observation for inspection, data detection or may be a second partially or fully reflective surface where it is useful to produce a resonant behavior at a particular point **15A**. An imaging lens **14** is situated within the resonator to image surface **12A** onto a surface of interest **15**. For a Gaussian beam, the above-mentioned condition is achieved when both surfaces **12A** and **15** are located in the two focal planes of lens **14**. In the configuration of **Figure 2A**, illumination introduced through partially reflective surface **12A** and plate **12** is focused at point **15A** and point **15A** is imaged across an area of partially reflective surface **12A** Area **13** of partially reflective surface **12A** is shown in balloon **16** to illustrate the generally circular profile of the image area of point **15A**.

Partially reflective surface **12A** is positioned at a distance above point **15A** such that a resonance is produced by multiple internal reflections between point **15A** and partially reflective surface **12A** taking into account the differing optical path length through lens **14** from a resonator without a lens. The resonator of **Figure 2A** generally has the same level of resonance as a standard parallel plate Fabry-Perot resonator, but has advantages when resonance is introduced in a system where the resonance takes place between a large finite area and a single measuring point, such as in the inspection and data storage systems described in the above-incorporated patent applications.

In alternative to focusing lens **14** and setting the resonant distance with respect to a point on surface **15**, the resonant length may be set to a distance above or below surface **15** providing the roughness filtering features and height sensitive improved region described in "OPTICAL INSPECTION METHOD AND APPARATUS HAVING AN ENHANCED HEIGHT SENSITIVITY REGION AND ROUGHNESS FILTERING", with consequent improvement of imaging at a point by introducing an imaging lens to produce an optical system in accordance with the present invention. Since the focal depth of lens **14** is generally much larger than the optical distances between resonant points of resonator **10**, the resonant length may be adjusted by 10 or more resonances without

significantly defocusing the image of point **15A**. The ability to independently adjust resonant length without affecting the focus, permits filtering in accordance with the above-referenced roughness filtering techniques, as well as the enhanced phase measurements of the above-incorporated application entitled "OPTICAL MEASUREMENT AND INSPECTION METHOD AND APPARATUS HAVING ENHANCED OPTICAL PATH DIFFERENCE DETECTION".

Additionally, resonators in accordance with embodiments of the present invention may image a point on one reflective surface to another point on another reflective surface, an area on one reflective surface to an area on another reflective surface, as well as the depicted point to area imaging. Point-to-point imaging is useful for eliminating sensitivity to adjustment (tilt) of all surfaces, while point-to-area is useful for desensitizing the system on the area resonant side, while area-to-area (which is really many point to many point correspondence) is useful for image sensing (visual imaging or field imaging) or projection (as in mask projection for photolithography) as opposed to point measurement, which is generally used for phase coherent point detection measurements.

The effect of imaging lens **14** is to make the optical distance between point **15A** and partially reflective surface **12A**

zero, by providing a convergence that counters the propagation divergence that would otherwise occur in the illumination and return paths of a beam introduced through partially reflective surface **12A** and reflected from point **15A** back to partially reflective surface **12A**. Without the use of lens **14**, existing systems generally need to use very short distances between resonator surface in both the systems described in the above-incorporated patent applications and in other resonator-enhanced optical systems. Especially when using a resonant system to detect small features of surface **15**, a small propagation distance is needed, as the divergence through the resonator determines the resolution of the system within the diffraction limitations of the other optics. While confocal resonators have been implemented in existing systems that can provide enhanced resonance at a point within the resonator, when inspecting (or reading data from a surface) and using the surface as one of the resonator plates, confocal resonance is not practical, as the surface being observed is not generally a focal curve, and if it is, a particular curved matching resonator element would have to be used to achieve a confocal resonator.

The resonant path in the above-described resonator can be set to the path between point **15A** and partially reflective surface **12A**, or the resonance may be produced by the total path

from partially reflective surface **12A** through imaging lens **14** to point **15A** and back through imaging lens **14** to partially reflective surface **12A**. In addition to the point-focused resonator embodiments described above, the lens inside the resonator may also be adjusted to image an area of one reflective surface onto another surface, providing an imaging capability.

Sensitivity of the resonator of the present invention is not critical with respect to lens **14** or partially reflective surface **12A**. Due to the Image-Object relationship generated by lens **14**, the positioning of the lens is less critical than the positioning of the resonator plates. Likewise, the sensitivity to aberration or other defects in lens **14** is low, since the resonance is between point **15A** and partially reflective surface **12A**, and therefore the defects of lens **14** will not resonate. The resonator is most sensitive to point **15A**, which is desired in systems designed to optically observe a point (or small region). Sensitivity at partially reflective surface **12A** is also generally low, as the resonance that is generated between point **15A** and partially reflective surface **12A** is spread over area **13**.

Imaging lens **14** can also be of any magnification or demagnification since the lens system transfer function is bi-

univocal (i.e., having a point to point unique spatial transformation). Thus, both focusing systems (imaging at infinity - infinite conjugation ratio) for observing a point **15A** as described above can be implemented, as well as finite conjugation ratio systems for imaging a fixed area onto partially reflective surface **12A** can be implemented. Detailed descriptions will be provided in the exemplary embodiments described below.

An alternative embodiment of a resonator in accordance with the present invention is of particular interest, which is illustrated in **Figure 2B**. A partially reflective surface **12B** deposited on a lens **14A** having a convex surface **14B** is used in a similar fashion as the resonator of **Figure 2B** and is configured to image point **15A** on area **13A** (shown in balloon **16A**) of partially reflective surface **12B**. The advantage of the resonator of **Figure 1B** is that partially reflective surface **12B** and lens **14A** are provided as one assembly, although it is no longer possible to separately set the focal point of lens **14A** at point **15A** independent of the resonant wavelength of the resonator.

Both embodiments of the resonator depicted in **Figures 2A** and **2B** are applicable in the systems described below, although resonators having a separate partially reflective surface and

lens will be described, it should be understood that within the limitation stated above for the tunability, either configuration may be used.

Another possible configuration for an infinite conjugation ratio implementation is illustrated in the **Figure 2C**. In the illustrated configuration, an illumination **I** is parallel but offset relative to the optical axis of the system. Due to the imaging properties of the system, rays bounce forth and back between two areas of partially reflective mirror **12C**, supporting a resonance. In the depicted configuration, lens **14C** is acting as a relay, imaging mirror **12C** onto the surface, then again with an offset, imaging surface onto mirror **12C**. Reflection continues, supporting resonance. An advantage of the implementation of **Figure 2C** is the use of a single mirror for both reflection end-points of the resonator, a lateral offset that allows detection set apart from an incident laser beam, and a lower sensitivity to misalignments due to a "perfect optical system" configuration (the source is imaged onto itself).

Referring now to **Figure 3**, an optical system **20** in accordance with a first system embodiment of the present invention is depicted. An illumination subsystem **22**, generally a collimated laser source, is coupled to partially reflective

surface **12A** on plate **12** via a beamsplitter/quarter-wave plate combination **26** acting as an optical isolator. The collimated illumination beam **28A** is thus directed through optical path **28B** into the resonator formed by partially reflective surface **12A**, imaging lens **14** and surface **15** point **15A**. Within the resonator, the collimated illumination provided through optical path **28B** is focused by imaging lens **14**, providing point illumination at point **15A**, which is then reflected by surface **15** back along optical path **28C** to imaging lens **14**, which images surface **15** onto partially reflective surface **12A**, again through optical path **28B**. The return image is then coupled through isolator/beamsplitter **26** through optical path **28D** into detection subsystem **24** which can measure the phase and/or amplitude of the returned image of point **15A**.

System **20** has a resonance supported by surface **15** point **15A** and its image on partially reflective surface **12A**. The optical path length between point **15A** and partially reflective surface **12A** is set so that the multiple internal reflections arriving at partially reflective surface **12A** constructively interfere as the optical path length between point **15A** and its image is a multiple of a half-wavelength of the illumination provided by illumination subsystem **22**, as the total return path is twice the

optical path length between point **15A** and its image on partially reflective surface **12A**.

A scanning subsystem **29**, mechanically coupled to surface **15** and/or optical head **27** containing all or some of optical system **20** components can be used to scan point **15A** over surface **15** providing for surface **15** inspection or data extraction from an optical media comprising surface **15**.

Referring now to **Figure 4**, an optical system **30**, in accordance with a second system embodiment of the present invention is shown. System **30** is similar to the above-described system **20**, so that only differences in structure and operation will be described below. In contrast to system **20** of **Figure 3** (and similar to that depicted in **Figure 2C**) in system **30**, an illumination is offset with respect to a detection path. Illumination path **28A1** is directed at a partially reflective region **27A** of a mirror **27** and illumination proceeds along optical path **28B1** to lens **14**.

Optical path **28C1** between imaging lens **14** and point **15A** is then angled by imaging lens **14** at point **15A** surface **15**. The reflection from point **15A** returns along optical paths **28C1** and **28C2** and is imaged by imaging lens **14** onto partially reflective

surface **12A**. Light reflected back on optical path **28C1** returns along optical path **28B1** and sent by quarter-wave plate **26A** and mirror **27** (via beam-splitting region **27A**) to a detection subsystem **24** along optical path **28D**, while light reflected along optical path **28C2** returns along an optical path **28B2** at a offset equal to and opposite side of the optical axis of lens **14** from optical path **28B1**. Detection subsystem **24A** receives the returned image of point **15A** along optical path **28B2** and measures the returned light from optical path **28F** via reflection of the fully-reflective portion of mirror **27**. Due to the conservation of energy within optical system **30**, the light detected by detection subsystems **24** and **24A** will be complementary in amplitude.

Within the resonator, the illumination provided through optical path **28B1** is focused by imaging lens **14**, providing off-axis point illumination at point **15A**, which is then reflected by surface **15** back along optical paths **28C1** and **28C2** to imaging lens **14**, and images the reflection onto partially reflective surface **12A**, through optical paths **28B1** and **28B2**. System **30** has a resonance supported twice by areas (which may overlap or be separate, depending on the scale of system **30** and the image sport size) on partially reflective surface **12A** via a reflection imaged through lens onto point **15A** of surface **15** and back to

partially reflective surface **12A**. Surface **15** acts as an intermediary reflective surface and not as a resonant surface within the resonator. As in system **20** of **Figure 3**, the resonant optical path length between point **12A** and itself is set so that multiple internal reflections arriving at partially reflective surface **12A** constructively interfere, that is, the optical path length between point **15A** and partially reflective surface **12A** is still a multiple of a half-wavelength of the illumination provided by illumination subsystem **22**, as the total path from partially reflective surface to point **15A** and back is twice the optical path length between point **15A** and its image on partially reflective surface **12A** as described in **Figure 1**.

Referring now to **Figure 5**, an optical system **40**, in accordance with a third system embodiment of the present invention is shown. System **40** may also include a mechanical or electro-mechanical scanning system as depicted in figures 1 and 2, but is omitted for clarity of depiction. System **40**, rather than imaging a point on surface **15**, images an area **15B** onto an area of partially reflective surface **12A**, providing an image of each point within area **15B** imaged to a corresponding point on partially reflective surface **12A**. In order to improve illumination by removing the image of the source from the object plane, a second lens, focusing lens **14B**, is added to the

resonator. Illumination is provided from illumination subsystem **22** through an isolator **26B** as used above in system **20**.

Imaging lens **14** images a reflection of a point in area **15B** into a converging beam in optical path **28G** onto a corresponding point on surface **12**. Lens **14B** is a field lends that provides good coverage of the resonating field of view. A third lens **45** outside of the resonator, images partially reflective surface **12A** onto detection subsystem **44**. Thus the third depicted embodiment is a system **40** capable of visual observation by a purely optical system (inspection microscope) as well as electro-optical imaging systems.

Resonance is supported between the area on partially reflective surface **12A** and area **15B** on surface **12**, so that multiple optical path length between area **15B** and partially reflective surface **12A** is set so that the multiple internal reflections arriving at partially reflective surface **12A** constructively interfere and the multiple internal reflections arriving at area **15B** constructively interfere, as the optical path length between each point in area **15B** and the corresponding point on partially reflective surface **12A** is a multiple of a half-wavelength of the illumination provided by illumination subsystem **22**. Partially reflective surface **12A** may include an

optional mask as described above with reference to **Figure 1**, for reproducing an image of the mask at area **15B.** The resonance of the system provides for near-perfect reproduction of the mask at area **15B.**

An advantage of the finite conjugation ration system **40** depicted in **Figure 5**, is that system **40** has a low sensitivity to adjustments, as well as the ability to measure images rather than single points.

Any of the above-described structures can be used to provide multiple cascaded resonators by using multiple lens-enhanced resonators and/or non-lens resonators in combination. Further, a mask can be incorporated within any of the above systems for reproducing an image of the mask on another surface. The partially reflective surface can be placed as close to the optics as need or can be incorporated in the optics as shown in the resonator of **Figure 1B.** In the imaging system of **Figure 4,** the partially reflective surface may be provided as a coating on a planar side of a plano-convex focusing lens (as opposed to a coating on the imaging lens).

While the invention has been particularly shown and described with reference to the preferred embodiments thereof,

it will be understood by those skilled in the art that the foregoing and other changes in form, and details may be made therein without departing from the spirit and scope of the invention.